

Analysis and test verification of influencing factors of strain balance force measurement

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Abstract. As an important component of wind tunnel force test, strain balance is very important to ensure its measuring accuracy. The operation mode of continuous wind tunnel will lead to the existence of temperature gradient in strain balance, which will generate thermal stress inside and affect the accuracy of wind tunnel test data. Starting from the actual work, this paper selects a strain balance as the research object, defines four commonly used material properties, uses ANSYS workbench to do finite element simulation, uses orthogonal test method to analyze the influence of each material parameter on the thermal strain output of the balance, and finds out the best material. At the same time, the strain balance prepared by the best material was verified by wind tunnel test. The finite element analysis results show that the influence of each material parameter on the thermal strain output of the balance is hot wire expansion coefficient, elastic modulus, specific heat capacity, density and thermal conductivity. The strain balance prepared with material 1 can effectively reduce the heat output of the balance. The experimental verification shows that the output potential signals of each element of the strain balance prepared with material 1 are relatively stable in the face of drastic temperature rise changes of the balance body and large temperature gradient, and meet the advanced standard of the national military standard.

Keywords: Strain balance; Continuous wind tunnel; Finite element analysis; Material properties; Wind tunnel test.

1. Introduction

Since the beginning of the new century, the domestic aviation and aerospace industry has developed rapidly, which reflects the comprehensive strength of a country, and has always been the focus of the development of aviation powers. Wind tunnel test is one of the most important links in the development of aircraft. Strain balance, as an important component of wind tunnel test, directly measures the aerodynamic load of aircraft. Strain balance is mainly composed of balance element (elastic element), strain gauge and measuring circuit [1]. During the wind tunnel force measurement test, the strain balance directly senses the multi-dimensional aerodynamic load of the measured model, so the force measuring element and the pasted strain gauge produce elastic deformation together, resulting in the change of the resistance value of the strain gauge, which breaks the balance of the original Wheatstone bridge. The generated resistance change is converted into the change of the bridge voltage through the Wheatstone bridge. Finally, after the A/D conversion, Wind tunnel test data were obtained [2, 3].

However, there are temperature effects in the strain balance in actual working conditions, which mainly include two kinds: zero temperature effect of strain balance and temperature effect of strain balance sensitivity. These two kinds of temperature effects are especially obvious in the wind tunnel test of small scale balance. This problem has affected the accuracy of wind tunnel force test data. Therefore, how to solve the effect of temperature on wind tunnel force test data is very important.

Scholars at home and abroad have studied the influence of temperature effect on balance force measurement. Since 1978, relevant researchers in the Netherlands, Germany and the United States have respectively studied the influence of temperature gradient on the force measurement of the balance, and confirmed that temperature change is the main reason for the existence of temperature effect in the balance, and temperature gradient is the main factor affecting the measurement accuracy

[4-6]. In order to reduce the thermal zero drift of strain balance output during force measurement, Masataka Kohzai of Japan proposed a preheating method. After preheating, the balance output gradually changes, thus reducing the correction error of thermal zero drift [7-8]. In order to solve the zero-point temperature effect of the balance, Li Chun et al. selected a variety of materials to carry out the temperature compensation test and the final results reached the expectation [9]. Considering the influence of temperature on the strain balance force measurement, Miao Lei et al. established the thermodynamic coupling loading system of strain balance, and the test results showed that the comprehensive loading error of each component of the balance was better than 0.3% [10]. Wang Yanyang et al. analyzed the causes of temperature effect in continuous wind tunnels and proposed a method to solve the zero-point temperature effect of balance, and the final results reached the relevant technical indexes [11].

To sum up, scholars at home and abroad have proved the existence of temperature effect in wind tunnel force testing, but most of them directly conducted compensation test research for the purpose of studying material parameters in this aspect. In view of the problems in the above tests, based on the continuous wind tunnel, the influence of material properties on the axial load-thermal strain output of the balance was studied. Four different materials were selected for finite element analysis using the thermosolid coupling module of ANSYS workbench, and the properties of each material were explored by orthogonal test method to obtain the best material properties parameters. It provides the basis for material selection of wind tunnel balance. Then the experiment is conducted to verify whether the balance prepared with the best material can solve the influence of temperature effect on the wind tunnel force test.

2. Experimental materials and methods

2.1. Finite element analysis

CATIA was used to model a wind tunnel balance. In order to ensure the accuracy of finite element calculation, the model should be completely consistent with the real size. The three-dimensional model of strain balance is shown in Figure 1(a). The 3D model was saved in stp format and imported into ANSYS Workbench. Before the balance model is analyzed and calculated, the balance should be meshed. Mesh module in ANSYS Workbench is used for mesh partitioning. The result is 87,508 grids and 164,300 nodes. The final meshing effect is shown in Figure 1(b).

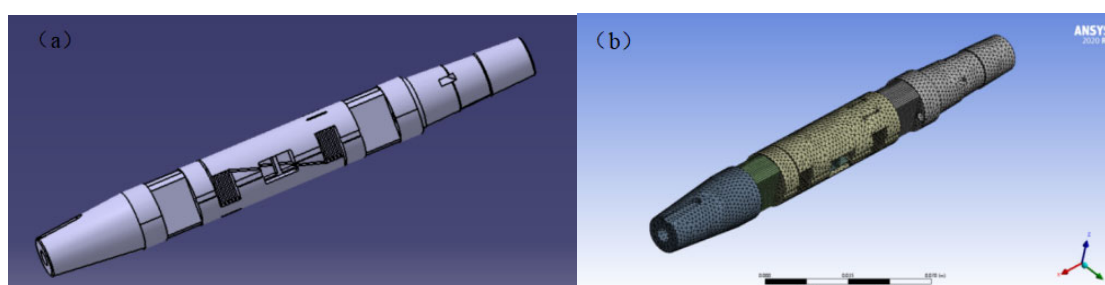


Figure 1. Strain balance model (a); Balance model after meshing (b).

For this finite element calculation, temperature input conditions were set: the front cone of the balance was used as the base point of temperature gradient, and the initial temperature of the base point was 22°C, which uniformly rose to 50°C within 360s, and the temperature was controlled 360s. Finite element analysis was performed using the Transient Thermal and Static Structural modules of ANSYS Workbench to calculate the thermal strain output of the balance axial force element.

2.2. Wind tunnel test

2.2.1. Experimental equipment

In order to study the temperature effect of strain balance, an experiment was carried out in FL-61 wind tunnel to test the influence of non-uniform temperature distribution in wind tunnel on the

temperature effect of strain balance. This test mainly consists of two parts, one is to use the heating belt for heating and natural cooling test, the other is to use FL-61 continuous wind tunnel for force measurement test. FL-61 wind tunnel was used in this test. FL-61 wind tunnel is a sub-, Trans-and super-trisonic continuous wind tunnel. The cross section size of the test section is 0.6m×0.6m, and the total length of the test section is 2.7m. The specific technical data of the strain balance used are shown in Table 1. The J-7 model adopted in the test is an all-metal model designed and processed according to the J-7 aircraft 1:23 reduction ratio. In addition to the flat tail and rear fuselage as a whole, there is no gap to simulate the real aircraft, and the appearance is basically all simulated. This test includes heating and natural cooling of heating belt. See Figure 2 for the real picture of heating belt and aircraft model.

Table 1. Design load, calibration load and comprehensive loading error of balance

Item/unit	Y	M_Z	M_X	X	Z	M_Y
Design load (N,N·m)	1700	80	20	200	400	40
Calibration load (N,N·m)	1680	78	20	200	400	39
Comprehensive loading error (%F.S.)	0.15	0.15	0.50	0.22	0.34	0.16



Figure 2. Real picture of heating belt and J-7 model

2.2.2. Test method

The heating belt test is carried out in the hole wall test section when there is no wind. The heating belt winding model is used to heat the model and heat is transferred to the balance. When the heating reaches about 55°C, the heating is turned off to the power supply so that it can be cooled naturally. The winding position of the heating belt on the model is mainly concentrated in the position where the front cone of the balance is connected with the model, as shown in Figure 3.

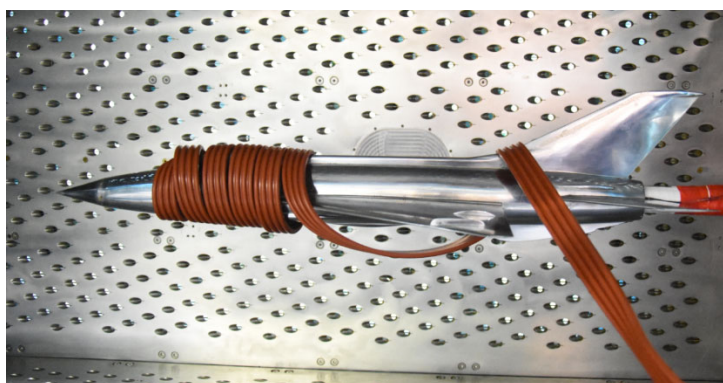


Figure 3. Heating belt on the model winding form of the physical picture.

The temperature effect blowing test of strain balance was carried out in the wall test section, the wind speed was 0.8Ma, the Angle of attack $\alpha = -4^\circ, -2^\circ, 0^\circ, 2^\circ, 4^\circ$, and the sideslip Angle $\beta = 0^\circ$. By controlling the total temperature of the flow field to the specified temperature, the balance data is collected and the temperature effect of the strain balance is obtained.

In the whole test, no matter it is a blower test or a heating test in the heating belt, the temperature of the balance body needs to be measured in this process. The above temperature is measured by PT100 temperature sensor with 3 PT100 on the balance. They are denoted as T1, T2 and T3 respectively. T1 is placed in the front end, T3 is placed in the middle of the balance body, and T2 is placed in the back of the balance body (the front cone of the balance is the front, and the back cone is the back).

2.2.3. Calculation of coefficient under wind shafting

The attitude Angle of FL-61 wind tunnel model is obtained by correcting the pitch Angle of scimitar mechanism and the elastic Angle of balance. The nominal sideslip Angle of the model is β_m , equal to 0, and the nominal attack Angle of the model is α_m . The calculation formula of coefficient under wind shafting is as follows:

$$C_{yw} = \frac{N_{yw}}{qS} \quad (1)$$

$$C_{zw} = \frac{N_{zw}}{qS} \quad (2)$$

$$C_{xw} = \frac{N_{xw}}{qS} \quad (3)$$

$$C_{mxw} = \frac{M_{xw}}{qSL} \quad (4)$$

$$C_{mzw} = \frac{M_{zw}}{qSL} \quad (5)$$

$$C_{myw} = \frac{M_{yw}}{qSL} \quad (6)$$

Where, N_{yw} , N_{zw} and N_{xw} are lift force, side force and axial force of wind shafting respectively. M_{xw} , M_{zw} and M_{yw} are rolling moment, pitching moment and yaw moment of wind shafting respectively. C_{yw} , C_{zw} , C_{xw} , C_{mxw} , C_{mzw} and C_{myw} are respectively lift coefficient of wind shafting, side force coefficient, axial force coefficient, roll moment coefficient, pitch moment coefficient and yaw moment coefficient. q is the incoming flow pressure, S is the model reference area, and L is the model spread.

3. Results and analysis

3.1. Finite element analysis

In order to explore the influence of material properties on the axial load-thermal strain output of the balance, orthogonal test was used as the research method. The strain balance of four different materials is taken as the research object, and the influence of material density, thermal conductivity, specific heat capacity, hot-wire expansion coefficient and elastic modulus on axial force output is comprehensively considered. The orthogonal test table of five factors and four levels is designed, as shown in Table 2. At the same time, Table 2 also shows the material properties of four different materials, and the horizontal combination table is shown in Table 3.

Table 2. Horizontal factor table (Material property.

	Density $\rho/(\text{g}\cdot\text{m}^{-3})$ (A)	Thermal conductivity $\lambda/(\text{W}\cdot\text{m}^{-1}\cdot^{\circ}\text{C}^{-1})$ (B)	Specific heat capacity $C/(\text{J}\cdot\text{Kg}^{-1}\cdot^{\circ}\text{C}^{-1})$ (C)	Coefficient of linear expansion $\alpha/(10^{-6}\cdot^{\circ}\text{C}^{-1})$ (D)	Modulus of elasticity $E/(\text{GPa})$ (E)
1	8.18(1)	14.6(1)	515(1)	3.454(1)	140(1)
2	7.93(2)	17.9(2)	423(2)	10.7(2)	180(2)
3	7.78(3)	18.1(3)	464(3)	11.2(3)	200(3)
4	8.00(4)	16.5(4)	481(4)	8.4(4)	160(4)

Table 3. Horizontal combination table.

	(A)	(B)	(C)	(D)	(E)
1	8.18(1)	14.6(1)	515(1)	3.454(1)	140(1)
2	8.18(1)	17.9(2)	423(2)	10.7(2)	180(2)
3	8.18(1)	18.1(3)	464(3)	11.2(3)	200(3)
4	8.18(1)	16.5(4)	481(4)	8.4(4)	160(4)
5	7.93(2)	14.6(1)	423(2)	11.2(3)	160(4)
6	7.93(2)	17.9(2)	515(1)	8.4(4)	200(3)
7	7.93(2)	18.1(3)	481(4)	3.454(1)	180(2)
8	7.93(2)	16.5(4)	464(3)	10.7(2)	140(1)
9	7.78(3)	14.6(1)	464(3)	8.4(4)	180(2)
10	7.78(3)	17.9(2)	481(4)	11.2(3)	140(1)
11	7.78(3)	18.1(3)	515(1)	10.7(2)	160(4)
12	7.78(3)	16.5(4)	423(2)	3.454(1)	200(3)
13	8.00(4)	14.6(1)	481(4)	10.7(2)	200(3)
14	8.00(4)	17.9(2)	464(3)	3.454(1)	160(4)
15	8.00(4)	18.1(3)	423(2)	8.4(4)	140(1)
16	8.00(4)	16.5(4)	515(1)	11.2(3)	180(2)

Figure 4 shows the results calculated from Table 3. It can be concluded that when the input conditions are the same and only the balance material parameters are changed, the variation law of axial load-thermal strain output with time is highly consistent. The thermal strain output reaches its maximum value around 360s and then decreases gradually.

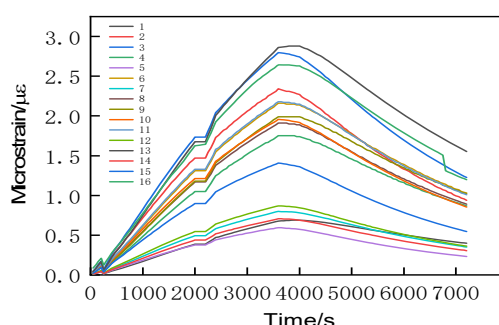


Fig 4. Finite element calculation result.

According to Figure 4, the axial mechanical and thermal strain output at 360S is analyzed, and the analysis results of orthogonal test are shown in Table 4. According to the K-factor size, the optimal horizontal parameters of each factor can be obtained, which are respectively A1, B2, C4, D1 and E4. By comparing the size of the R-factor, it can be concluded that the influence of the properties of each material on the output of axial mechanical and thermal strain is in the order of hot-wire expansion coefficient, elastic modulus, specific heat capacity, density and thermal conductivity from high to low. Therefore, a lower thermal expansion coefficient can effectively reduce the thermal strain of the

axial force element. That is, on the premise of satisfying the material strength, the material with low thermal expansion coefficient can effectively reduce the heat output of the strain balance measuring bridge.

Table 4. Orthogonal experimental analysis table.

Range analysis	Resistance element thermal strain output at 3600s				
	(A)	(B)	(C)	(D)	(E)
k1	5.2588	5.8538	7.2938	2.9445	5.6681
k2	5.3136	5.5096	4.8436	8.8404	7.0534
k3	5.7627	6.6071	6.9716	6.4162	7.1217
k4	7.1951	5.5597	4.4212	5.3291	3.687
K1	1.3147	1.4635	1.8235	0.7361	1.4170
K2	1.3284	1.3774	1.2109	2.2101	1.7634
K3	1.4407	1.6518	1.7429	1.6041	1.7804
K4	1.7988	1.3899	1.1053	1.3323	0.9218
R	0.4841	0.2744	0.7182	1.4740	0.8587
Range analysis	A1	B2	C4	D1	E4

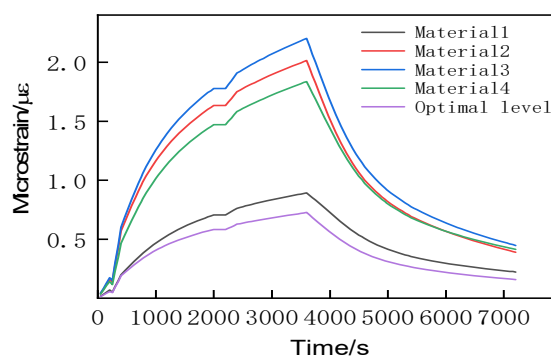


Fig 5. Finite element calculation result.

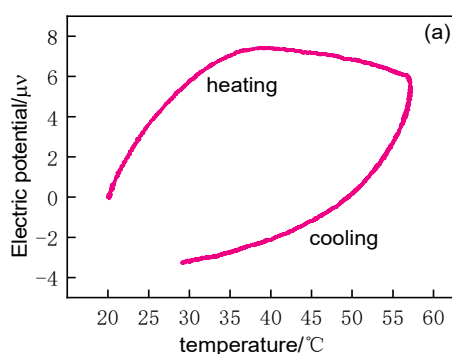
FIG. 5 is a comparison of the axial mechanothermal strain output of the four material balances and the balance with optimal horizontal material performance. The thermal strain output of material 1 and optimal level material balance is smaller than that of the other three materials, and the output of the two materials is close. Therefore, the balance prepared by material 1 can effectively reduce the influence of temperature effect on the measured data of the balance.

3.2. Finite element analysis

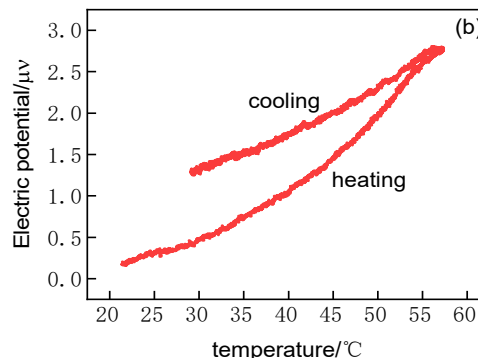
3.2.1. Difference analysis of heating and cooling processes

FIG. 6 shows the variation curve of the electric potential of each element of the balance with the temperature of T1 during the rise and fall of the heating zone heating test. It can be seen that the voltage of each element of the balance presents two different processes during the rise and fall of the balance body. The final result is that there is a certain deviation in the balance data collected at the same temperature in the heating and natural cooling process under the experimental state of heating and natural cooling in the heating belt. The phenomenon that each element of the balance body has differences in the process of rising and cooling is not unique to this material, as is the case with F141 steel. From the phenomenon analysis of the source may have two: one is due to the temperature change rate is different; another factor is that the scales themselves differ in how they rise and how they cool.

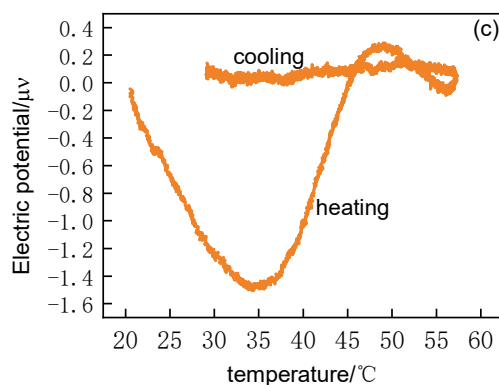
Since this type of balance adopts constant temperature zero temperature compensation, the specific reason why the resistance element of the balance only changes by 2 units in the process of such a large temperature rise is not determined whether it is the Yin steel material or the physical compensation. So wind tunnel tests are needed to verify this further.



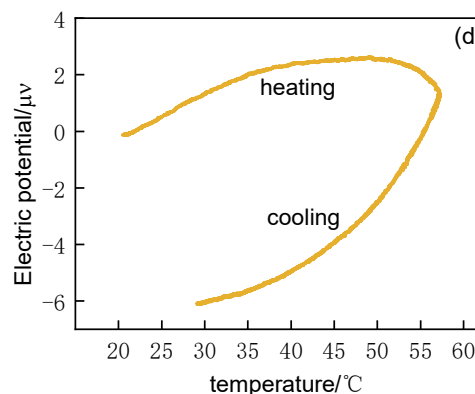
(a) Potential-temperature curve of U1 element.



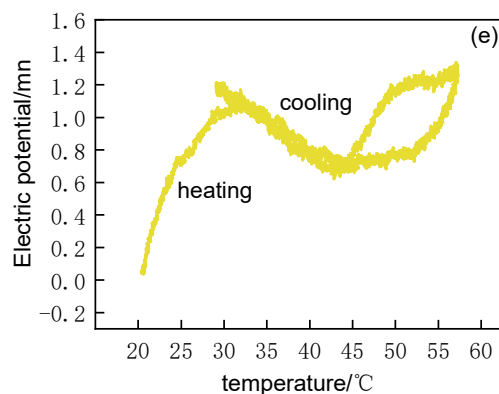
(b) Potential-temperature curve of U2 element



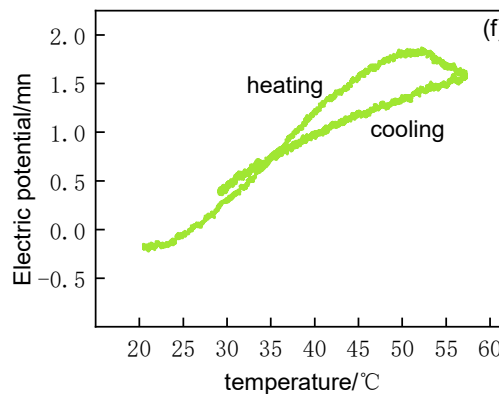
(c) Potential-temperature curve of U3 element.



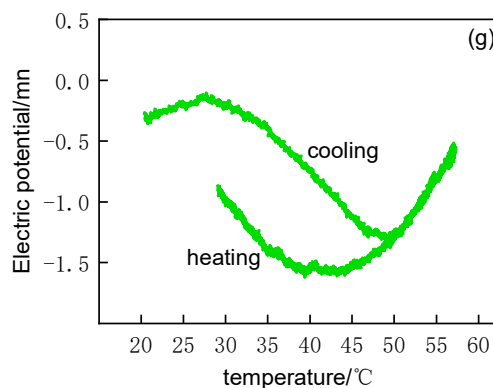
(d) Potential-temperature curve of U4 element



(e) Potential-temperature curve of U5 element.



(f) Potential-temperature curve of U6 element.

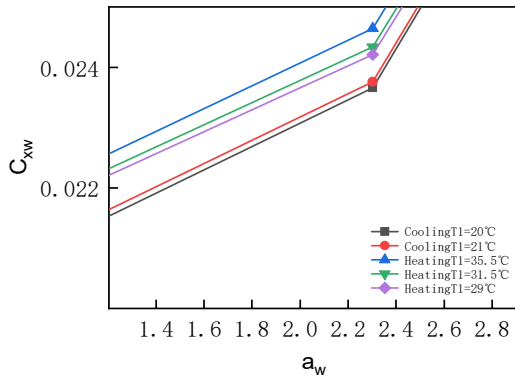


(g) Potential-temperature curve of U7 element

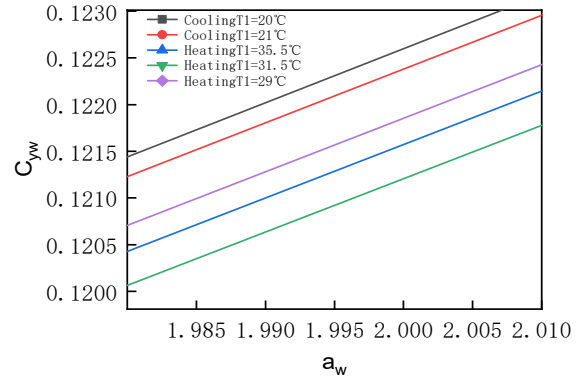
Fig 6. Variation of potential output of each element of strain balance in heating zone test.

3.2.2. Wind tunnel test

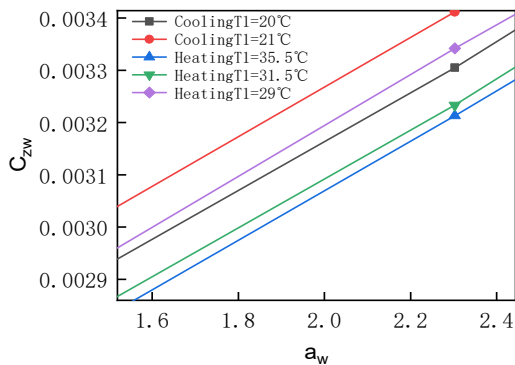
During the test, the force measurement data at 29°C, 31.5°C and 35.5°C were collected when the temperature at the front end of the balance T1 increased from 23°C to 35.5°C. Meanwhile, the force measurement data at the temperature at the front end of the balance T1 dropped to 21°C and 20°C were collected. The test results are shown in Figure 7. It can be seen from Figure 7 that in the same heating or cooling process, the force measurement data of each element of the ardent steel balance are less affected by temperature, but there is a significant deviation between the force measurement data in the heating and cooling process, which is consistent with the phenomenon and conclusion of the heating belt test.



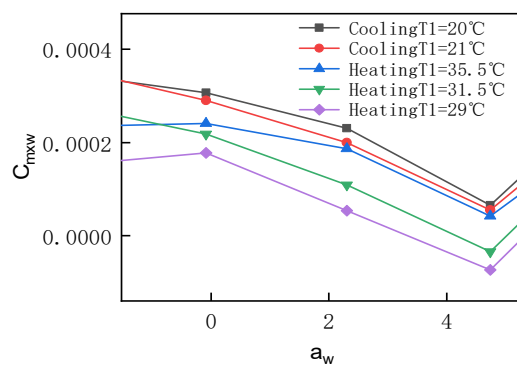
(a) Wind shafting resistance coefficient - Angle of attack 2°curve.



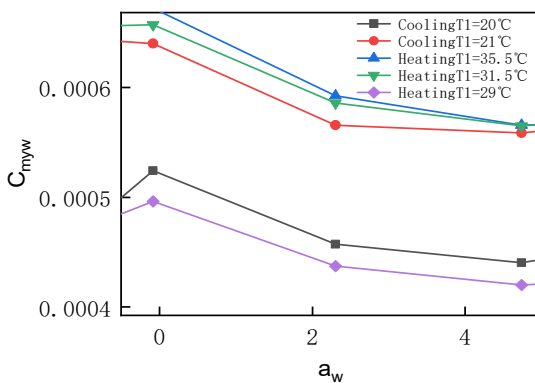
(b) Wind shafting lift coefficient - Angle of attack 2°curve



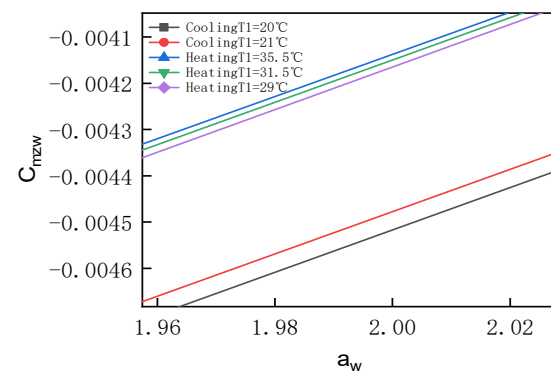
(c) Wind shafting side force coefficient - Angle of attack 2°curve.



(d) Wind shafting rolling torque coefficient -angle of attack 2°curve.



(e) Wind shafting yaw moment coefficient -angle of attack 2°curve.



(f) Wind shafting pitch moment coefficient -angle of attack 2°curve

Fig 7(a, b, c, d, e, f) The influence curve of the uneven temperature distribution of the balance body on the balance effect.

4. Conclusion

(1) According to the finite element analysis, the influences of material parameters on axial force of strain balance are hot-wire expansion coefficient, elastic modulus, specific heat capacity, density and thermal conductivity in sequence. And material 1 was selected as the material of the balance prepared to carry out follow-up verification work

(2) According to the heating and cooling experiments of the heating belt, it can be seen that there are great differences between the heating and cooling processes of the balance prepared by material 1. From the phenomenon analysis, there may be two reasons: one is due to the difference of temperature change rate; another factor is that the scales themselves differ in how they rise and how they cool. But this phenomenon is not a matter of personality and needs to be verified by wind tunnel tests.

(3) According to the wind tunnel test, when the elevation Angle is between -4° and 4° , both under the condition of temperature rise and temperature drop, the material 1 balance is less affected. In addition, there are some differences in the data of temperature rise and temperature drop, which verifies the phenomenon of heating and cooling experiments in the heating belt.

(4) To sum up, when the balance prepared with material 1 faces drastic temperature rise changes of the balance body and huge temperature gradient, the output potential signal is relatively stable, which can effectively overcome the influence of temperature gradient on the force measurement data. In addition, other materials with low thermal expansion coefficient can also be used to prepare the balance under the premise of satisfying the service strength.

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